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**Acquisition of Modular Low Earth Orbit Satellites for Improved
Intelligence Collection**

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September 2012**

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**ACQUISITION OF MODULAR LOW EARTH ORBIT SATELLITES
FOR IMPROVED INTELLIGENCE COLLECTION**

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Submitted in partial fulfillment of the requirements for the degree of

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ACQUISITION OF MODULAR LOW EARTH ORBIT SATELLITES FOR IMPROVED INTELLIGENCE COLLECTION

ABSTRACT

The primary objective of this study is to investigate and analyze improved multi-source intelligence (multi-INT) data collection through low latency, cross-communicating, modular low Earth orbit (LEO) satellites. This research examines the current acquisition process and system engineering approach to multi-INT data collection via command, control, communications, computers, and intelligence, surveillance and reconnaissance (C4ISR) satellites, specifically focusing on time (production time and system life) and cost. The project introduces several proposed low latency, cross-communicating, modular LEO satellite systems for improved multi-INT data collection. It then provides a comparison of geosynchronous Earth orbit (GEO) satellite life-cycle costs versus the life-cycle costs of LEO satellites and analyzes the maintainability, upgradeability, interoperability, reliability, and safety/security (MUIRS) benefits of smaller, faster-to-orbit satellites that could be launched in weeks or months.

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LIST OF ACRONYMS AND ABBREVIATIONS

1U CubeSat	1 unit Cuboid Satellite Spacecraft Unit
3U CubeSat	3 unit Cuboid Satellite Spacecraft Unit
5U CubeSat	5 unit Cuboid Satellite Spacecraft Unit
APB	Acquisition Program Baseline
AEHF	Advanced Extremely High Frequency
ALASA	Airborne Launch Assist Space Access
APUC	Average Procurement Unit Cost
C2	Command and Control
C4	Command, Control, Communications, and Computers
C4ISR	Command, Control, Communications, Computers, and Intelligence, Surveillance, and Reconnaissance
CCW	Center for Cyber Warfare
COI	Critical Operational Issues
CONOPS	Concept of Operations
COTM	Communications On The Move
COTS	Commercial Off-The-Shelf
CubeSat	Cuboid Satellite Spacecraft Unit, Form Factor: 1 kg, 100 mm ³
DARPA	Defense Advanced Research Project Agency
DoD	Department of Defense
DSCS III	Defense Satellite Communications System III
DT	Developmental Testing
EHF	Extremely High Frequency
Envisat	Environmental Satellite
ESA	European Space Agency
F6	Future Fast, Flexible, Fractionated, Free-Flying Spacecraft united by Information eXchange
F6TP	F6 Technology Package
FDK	F6 Developer's Kit
FOC	Full Operational Capability
FYDP	Future Years Defense Program

GAO	Government Accountability Office
GEO	Geosynchronous Earth Orbit
GIG	Global Information Grid
GPS	Global Positioning System
HEO	Highly Elliptical Orbit
IP	Internet Protocol
IR	Infrared
ISR	Intelligence, Surveillance, and Reconnaissance
ISS	International Space Station
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
MILCON	Military Construction
MUIRS	Maintainability, Upgradability, Interoperability, Reliability, and Safety/Security
MUOS	Mobile User Objective System
Multi-INT	Multi-Source Intelligence
NASA	National Aeronautics and Space Administration
Navstar GPS	Navstar Global Positioning System
OT	Operational Testing
PAUC	Program Acquisition Unit Cost
PM	Program Manager
R&D	Research and Development
RDT&E	Research, Development, Test & Evaluation
SATCOM	Satellite Communications
SBIRS	Space Based Infrared Systems
SeeMe	Space Enabled Effects for Military Engagements
SMAD	Space Mission and Analysis and Design
SV	Space Vehicle
TacSat	Tactical Satellite
TMOS	TSAT Mission Operations Systems
TSAT	Transformational Satellite Communications System
TSOC	TSAT Satellite Operations Centers

UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
UCR	Unit Cost Reports
UHF	Ultra High Frequency
USAF	United States Air Force
USD(AT&L)	Under Secretary of Defense for Acquisition, Technology, and Logistics
WCDMA	Wideband Code Division Multiple Access
WGS	Wideband Global SATCOM
XDR	Extended Data Rate

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I. INTRODUCTION

The use of satellites for multi-source intelligence (multi-INT) data collection allows the military to conduct intelligence, surveillance, and reconnaissance (ISR) on any target or area around the globe. The military advantages of deploying satellite sensor systems are undeniable, but the time, cost, and resources required to produce current command, control, communications, and computers (C4) ISR satellites are too great to meet operational needs and do not support maintainability, upgradability, interoperability, reliability, and safety/security (MUIRS) issues. A transition is needed from the existing single-satellite architecture to a constellation architecture of low-cost, small satellites, as depicted in Figure 1.

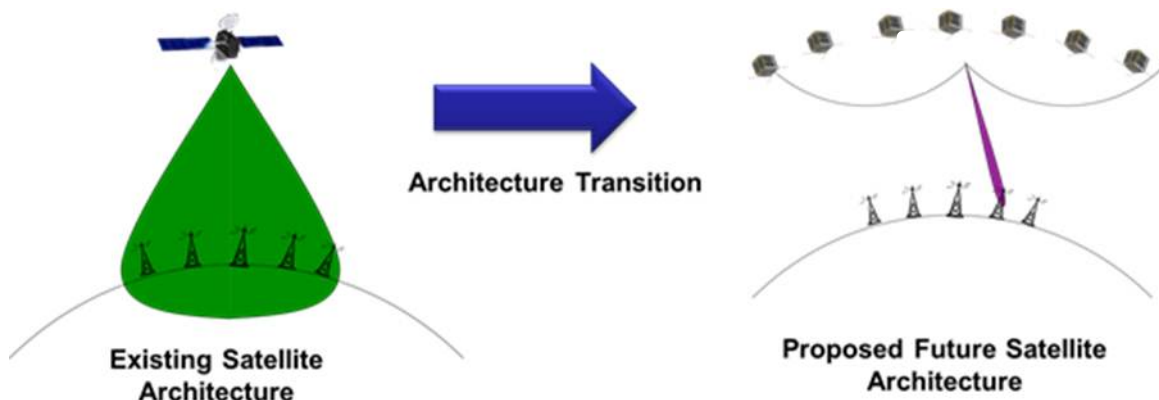


Figure 1. A Depiction of the Proposed Satellite Architecture Transition (After Goshorn, D., 2011)

In computer data networking arenas, a *constellation* (as a set of mobile nodes) can be called a *cluster* of mobile nodes. My electrical engineering thesis takes a networking approach for its small satellite constellation architecture and uses the cluster networking terminology (Staab, 2012). This joint applied project will refer to constellations of small satellites and clusters of small satellites interchangeably.

A. BACKGROUND

Most acquisition professionals agree that the current defense satellite acquisition process is excessively expensive. Satellite systems for C4ISR and communications will cost tens of billions of dollars more than the \$25 billion the military is spending on hundreds of thousands of new radios. The Army's program for a "war net" has a \$120 billion price tag on its own. After some 50 years of launching large, complex, multi-million-dollar spacecraft, the military and industry are rethinking the way satellites are built and acquired. During the past five decades, military and intelligence satellites have grown bigger because program managers wanted to fit as many capabilities as they could onto one spacecraft. It was expensive to launch these satellites and, once they went up, they could be in orbit for as long as 15 years. Congress has also singled out the cumbersome and expensive process of building satellites as a prime example of how major acquisition programs can go wrong. The costs of these programs have typically spiraled out of control during the past decade and delivery milestones have not been met, resulting in the tarnished reputation on Capitol Hill of the national security space community (Best, 2010).

One emerging future alternative is a system that is rapidly developed and delivered, and that can be quickly replaced (e.g., smaller, faster-to-orbit satellites that could be launched in weeks or months). A different concept would require launch systems that could lift off more quickly than current rockets and less complex spacecraft that could be assembled from off-the-shelf components in a plug-and-play fashion depending on mission requirements. Additionally, the demand for delivering high-quality software support has become paramount. In short, it has become the largest life-cycle cost driver and comprises a substantial portion of system risk. Developing supportable software is one of the most important criteria for ensuring success once a system has been fielded. Today's net-centric environment may be both enabling and multiplying these challenges. In the specific case of a satellite system, the changes, fixes, and upgrades that are always happening in other systems are limited by the inability to physically access the system—changes can only be accomplished through remote access. The defense establishment's ability to support major software-intensive systems is a

crucial mission requirement. The success of net-centric systems depends on it (Goshorn, R., Goshorn, D., Goshorn, J., & Goshorn, L., 2011).

Moore's law (the observation that over the history of computing hardware, the number of transistors on integrated circuits doubles approximately every two years resulting in the same computing capability in a device half the size of its predecessor) predicates utilizing a network of low-cost, small modular low Earth orbit (LEO) satellites rather than launching a heavy and expensive single satellite with a limited coverage area that is difficult or impossible to maintain, upgrade, or interface with new technology. The latter is also more vulnerable to data integrity loss and data interception because of the constant communication to terrestrial base stations. Unfortunately, heavy, single satellites need to be built to near ultra-reliability (99.999%) due to massive repair and replacement costs (B. Naegle, personal communication¹, August 2011).

A MUIRS analysis of low latency, cross-communicating, modular LEO satellites may reveal benefits in all categories. Low latency allows human-unnoticeable delays between an input being processed and the corresponding output providing real-time characteristics. Modularity and cross-communication allow for a scalable distribution of the processing resources in small satellites needed to produce the results that can be attained with a single large satellite. Small modular LEO satellites have a short life cycle and do not require maintenance once in orbit. Their short life cycle requires them to be replaced frequently and enables frequent upgrades and interoperability updates to maintain interoperability with new technologies in a constantly changing net-centric environment. The reliability required of each individual cross-communicating small satellite is far less than that required of a single large satellite—any failed satellite can be compensated by another satellite in its network. This configuration also enables greater safety and security for the system.

¹ From class lecture notes: *Acquisition of Embedded Weapon System Software* (MN3309), Graduate School of Business and Public Policy, Naval Postgraduate School.

B. PURPOSE AND OBJECTIVE

My objective in this joint applied project is to investigate and analyze improved multi-INT data collection through low latency, cross-communicating, modular LEO satellites. Specifically in this research, I examine the current acquisition process and system engineering approach to multi-INT data collection via satellite. In the project, I provide a comparison of geosynchronous Earth orbit (GEO) satellite life-cycle costs versus the life-cycle costs of LEO satellites and analyze the MUIRS benefits of smaller, faster-to-orbit satellites that could be launched in weeks or months.

The time, cost, and resources required to produce current command, control, communications, computers, and intelligence, surveillance, and reconnaissance (C4ISR) satellites are too great to meet operational needs and do not support MUIRS issues. I identify and enumerate the current C4ISR acquisitions process, specifically focusing on time (production time and system life) and cost. Additionally, I introduce several proposed low latency, cross-communicating, modular LEO satellite systems for improved multi-INT data collection. Finally, I justify the need for a transition to the acquisition of modular LEO satellite systems for improved multi-INT data collection by establishing and quantifying the benefits of such systems across the previously enumerated parameters as compared to the current C4ISR acquisition process.

C. APPROACH AND METHODOLOGY

As part of this research, I performed a system comparison of current GEO and proposed LEO C4ISR satellites, focusing on the following parameters: time (production time and system life), cost, and MUIRS attributes.

D. ORGANIZATION OF THIS REPORT

I introduce my topic with some background information and provide my purpose and approach in Chapter I. Chapter II comprises a literature review where I look at research that has been conducted to support my topic including satellite configuration and orbit selection, the systems engineering impact on cost, and commercial off-the-shelf alternatives.

I discuss defense satellite acquisition in Chapter III. I begin by offering a brief introduction to satellite orbits, and subsequently examine several current DoD satellite systems and their associated orbits and missions. Then, I offer several alternative systems with a different orbital selection.

In Chapter IV I present my analysis, focusing on the following parameters: time (production time and system life), cost, and MUIRS attributes. After my analysis, I provide my conclusions.

Chapter V contains my recommendations for a transition from the current systems discussed in Chapter III Section A to the alternative systems proposed in Chapter III Section B. These recommendations are supported by the comparative analysis and conclusions in Chapter IV. Finally, I conclude Chapter V by summarizing my work and offering areas for future work.

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II. LITERATURE REVIEW

There has been much research done in the area of satellite development, employment, improvement, and acquisition. During my literature review, I found several research papers that supported the objective of this project, which is to investigate and analyze improved multi-INT data collection through low latency, cross-communicating, modular LEO satellites. Specifically, the literature review confirms this project's three fundamental approaches of selecting LEO orbit, utilizing interconnected satellite constellations/clusters, and reducing system cost.

A. SATELLITE CONFIGURATION AND ORBIT SELECTION

In the first project I reviewed, *Tactical Satellite (TacSat) Feasibility Study: A Scenario Driven Approach* (Davis et al., 2006), I examined the cost and operational feasibility of developing a tactically controlled, operationally responsive satellite system. The study was a systems engineering capstone project and their approach made use of systems engineering practices based on the Space Mission and Analysis and Design (SMAD) process authored by Wiley J. Larson and James R. Wertz (1999). The authors chose a specific mission scenario, the Philippine Sea Scenario, to guide and bound the analysis. They used the scenario's high-level mission requirements to develop system requirements by conducting a gap analysis to discover which of the military requirements were not well served by existing tactical systems, such as Global Hawk. Then they selected appropriate payloads, orbits, and constellation sizes to meet the requirements. They also examined the concept of operations (CONOPS) and ground infrastructure established to support such a mission. Their scenario provided insights into operations and military utility as well as into the estimated costs for such a system.

The authors determined the natural shelf life of spacecraft and launch vehicles required for regularly scheduled launches of TacSats. They then calculated that those regularly scheduled launches would, in turn, lead to standardized yearly costs associated with their TacSat program scenario and also drive down per unit costs as more satellites were produced. They concluded that their proposed scenario would also encourage the

rapid development of new satellite technologies in a growing market. For cost estimation, they cited the procurement and operational costs of a TacSat system to be about \$65 million (2006 dollars) for a constellation of two satellites. They also noted that the operations costs of a tactical satellite system can be significantly less than the Global Hawk system when operated continuously over a one- to two-year period (Davis et al., 2006).

I found that their project supported several areas of my research. First, they found that the satellite orbits with the most utility for ISR are in LEO between 400–500 kilometers. Additionally, they determined that small satellite constellation sizes of two to four satellites provided acceptable ISR coverage and revisit times. Satellite “revisit” time is the time elapsed between observations of the same point on Earth by a satellite; it depends on the satellite’s orbit, target location, and swath of the sensor. Revisit is related to the same ground trace; a projection on to the Earth of the satellite’s orbit. Revisit requires a very close repeat of the ground trace. In the case of polar/hi inclination low Earth orbiting reconnaissance satellites, the sensor payload must have the “variable swath” to look longitudinally (east-west, or sideways) at a target, in addition to direct over-flight observation, looking nadir. Their findings support my proposal for a constellation architecture of small satellites in LEO orbit. Also, they demonstrated that there are tactical scenarios in which space capabilities provide military utility and cost effectiveness above what is provided by traditional tactical assets such as unmanned aerial vehicles (UAVs), particularly when large operational areas are involved and long periods of service are required.

B. SYSTEMS ENGINEERING IMPACT ON SATELLITE COST

Next, I examined the systems engineering approach to examine its impact on cost in satellite acquisition. In the thesis *A study on Improving United States Air Force Space Systems Engineering and Acquisition* (Stahr, 2006), the author studied the common issues that have impacted the ability of the United States Air Force (USAF) to cost effectively acquire satellite systems. He found that, indeed, systems engineering is a vital element of systems acquisition, yet, as a result of previous Department of Defense (DoD) and USAF

policies and practices, many government systems engineers lack the systems engineering and management skills required to successfully execute national security space programs.

I reviewed the author's analysis of the differences between the traditional DoD systems acquisition and the national security space systems acquisition processes in which he investigated previous national efforts to improve these processes. Again, I found that the author's conclusions supported my research. He used the results of his analysis and the findings from his review of successful and struggling space programs to discover trends. Specifically, he found that to improve the management skills of USAF systems engineers, and thereby improve the national security space systems acquisition process, the role of the government systems engineer should be defined as one of a risk manager, able to efficiently perform systems engineering in support of the space systems acquisition process (Stahr, 2006).

C. COMMERCIAL OFF-THE-SHELF ALTERNATIVE

In support of my first proposed alternative architecture of a constellation of commercial off-the-shelf (COTS) solutions for low-cost C4ISR, I reviewed a paper that sought to determine the possibility of an alternative for government-developed satellites that produce high-resolution imagery. The study focused on the concept of the U.S. government purchasing proven and successful commercial satellites with minimal non-recurring engineering costs to help augment current national systems. The benefit of this alternative is the reliability and affordability of a system that is currently used in space, therefore reducing a significant amount of risk as well as production time. A constellation of extremely small commercial satellites with short life cycles that are reconstituted on a monthly or quarterly cycle could also invigorate the commercial satellite work force and allow for better production of future systems. Conversely, the useful lifetime of GEO satellites averages about 14–15 years, a limit primarily imposed by the exhaustion of propellant aboard. The propellant is needed for “station-keeping”—maintaining the satellite in its orbital slot and in-orbit orientation, or attitude, so that its antennae and solar panels are properly pointed.

In the paper *A Commercial Architecture for Satellite Imagery* (Didier, 2006), Didier evaluated constellation design factors such as orbit types, number of satellites, and life cycle and ground segment implementation. He provided a coverage capability evaluation to determine how a commercial system would be able to fulfill national imagery collection requirements. He also created eight different constellation types, ranging in size from one to 12 satellites. His proposed satellite orbit analysis settled on a sun-synchronous polar elliptical orbit at 185 km by 700 km, using an existing commercial satellite with a 0.6 meter optic. This provided imaging with a resolution range between 10–37 inches. The largest constellation of 12 satellites provided a daily area collection of 43,000 square kilometers, 150 point images for a region the size of Iraq, and had an estimated \$1 billion to \$2 billion (2006 dollars) annual life-cycle cost. The revisit time for mid-latitude targets was approximately one day at 10-inch resolution (Didier, 2006).

D. COTS APPLICATIONS NEAR GEO

Having seen the utility of small COTS satellites in the previous literature, I looked at their ability to perform all the functions that larger satellites currently perform. The literature reviewed thus far has also intimated that small COTS satellites are less expensive, thus offering a lower cost/benefit risk in case they fail before the expected end of their mission design life. In the next paper I examined, *Smaller Satellite Operations Near Geostationary Orbit* (Erdner, 2007), Erdner observed the current technological ability of small satellites to perform covert space control and space situational awareness missions near geostationary orbit.

The author's investigation determined whether space-qualified COTS components and current technology could be used to build small, covert satellites. The largest satellite was sized by the author to be undetectable from Earth-based sensors. He subsequently selected CubeSat (a discrete but scalable 1 kg 100 x 100 x 100 mm cuboid spacecraft unit) sizes to determine how small a satellite could be built with COTS components and current technology to perform an ISR mission. He then performed a comparative analysis to determine how the small satellites could be cost effectively launched to orbit and a cost estimate to determine the entire life-cycle cost for each

satellite size, excluding launch and integration segments. Using that information, he determined the best satellite size to effectively conduct the optical survey mission was the 5U CubeSat constellation (Erdner, 2007).

E. COMPARISON OF COST EFFECTIVENESS

Finally, to support my advocacy for the use of small, interconnected clusters of LEO satellites to replace large, costly GEO satellites for multi-INT data collection offered in my introduction, I reviewed other lower altitude options. In Collier and Kacala's (2008) thesis, *A Cost-Effectiveness Analysis of Tactical Satellites, High-Altitude Long-Endurance Airships, and High and Medium Altitude Unmanned Aerial Systems for ISR and Communication Missions*, they offer that the DoD has focused its acquisition and procurement efforts on obtaining new communications and ISR platforms that can help lessen shortfalls and possibly exploit new, untapped resources.

Recently, there has been an increased focus on new technology, such as tactical satellites or high-altitude, long-endurance airships, as a way to increase communications and intelligence collection capacities. Likewise, advances in the capabilities of medium-altitude and high-altitude unmanned aerial systems (UASs) have resulted in a more prominent role for them on today's battlefield. Each of these vehicles has a unique niche in today's military, but the increasing capabilities of each are beginning to create some expensive, non-value-added overlap instead of offering desirable redundancy in military capabilities.

In the Collier and Kacala (2008) study, they conducted a cost-effectiveness analysis on these systems for use as a persistent communications and ISR platform. In particular, they measured the effectiveness of each in order to make a comparison. Using the strengths of each system from the comparison, they offered possibilities to increase the overall effective use of the three combined to maximize performance and cost. TacSats, because of their high altitude, had the greatest access but not the greatest coverage. ISR satellites are normally placed in LEO to maximize their imaging resolution. An example would be the IKONOS Earth-imaging satellite. At 680

kilometers altitude, the IKONOS has a very large access area; however, the images that IKONOS provides are typically 121 km²—much smaller than the actual access area (Collier & Kacala, 2008).

III. DEFENSE SATELLITE ACQUISITION

According to the U.S. Government Accountability Office (GAO) (Schwenn, Brink, Mebane, Seales, & Wintfeld, 2009), current weapon systems development programs are overrunning 42% in development cost and 25% in production cost, and are reaching initial operating capability, on average, 22 months behind schedule. These figures are not inconsistent with Norman Augustine's (1997) assessment of programs in the late 1970s and early 1980s, which, at completion, were 52% over in combined development and acquisition cost and 33% behind in schedule. The majority of the programs in the GAO report (Schwenn et al., 2009) were still in development and will presumably continue to fall further behind schedule and become more expensive, whereas the Augustine assessment used only completed programs, resulting in his higher numbers.

Collopy (2006) observed that the requirements allocation process naturally brings about cost growth and schedule delays of an order that is consistent with Augustine's observations. The effect occurs mainly because engineers who are asked to maximize the probability that a component will meet its allocated requirements will often find that the safest design is one that just barely meets most of the requirements. The result is a marginal system that needs several redesigns or major changes to achieve functionality. Every redesign increases system development time and cost, and most redesigns add to the unit production cost. On the other hand, a design team assigned to maximize design value is driven to choose designs that far exceed the levels of typical allocated requirements. The result is a robust design that is functional or nearly functional on the first go-round. This avoids long iterative development schedules and the attendant cost growth (Brown, Eremenko, & Collopy, 2009).

A. CURRENT SATELLITE SYSTEMS

1. A Brief Introduction to Orbits

There are essentially three types of Earth orbits: high Earth and geosynchronous Earth orbit (GEO); medium Earth orbit (MEO); and low Earth orbit (LEO). Low Earth

orbit starts just above the top of the atmosphere, while high Earth orbit begins about one tenth of the way to the Moon, as illustrated in Figure 2. Weather and communications satellites tend to have a high Earth orbit, farthest away from the surface. Satellites that orbit in a medium (mid) Earth orbit include navigation and specialty satellites, designed to monitor a particular region. Most scientific satellites, including NASA's Earth Observing System fleet and the International Space Station (ISS), have a low Earth orbit.



Figure 2. An Illustration of Classifying Orbits by Altitude (From Riebeek & Simmon, 2009)

The height of the orbit, or distance between the satellite and Earth's surface, determines how quickly the satellite moves around the Earth—the higher a satellite's orbit, the slower it moves. Figure 3 provides an illustration of orbital speed at selected altitudes. The length of each red arrow in the illustration represents the distance traveled by a satellite in an hour. An Earth-orbiting satellite's motion is mostly controlled by Earth's gravity. As satellites get closer to Earth, the pull of gravity gets stronger, and the satellite moves more quickly. A typical LEO satellite, for example, requires about 90 minutes to orbit the Earth.

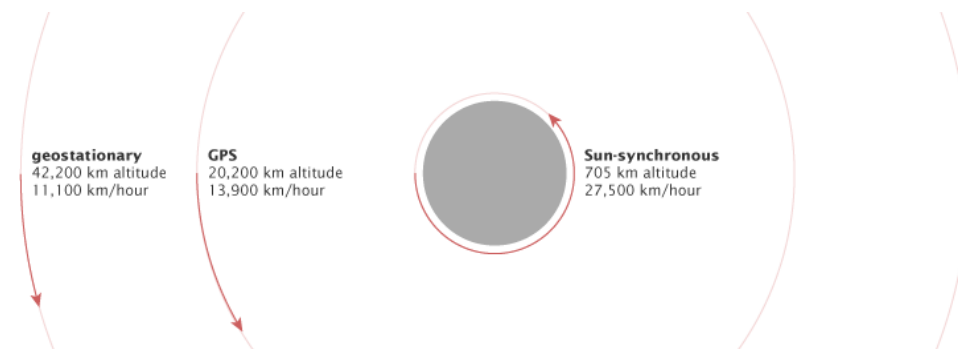


Figure 3. An Illustration of Orbital Speed at Selected Altitudes (From Riebeek & Simmon, 2009)

Certain orbital altitudes have special properties, like a geosynchronous orbit, in which a satellite travels around the Earth exactly once each day. For this reason, weather satellites are typically placed in GEO to maintain a constant view of the Earth for observing weather patterns. At 384,403 kilometers from the center of the Earth, the moon completes a single orbit in 28 days.

2. DoD Satellite Systems in GEO and MEO

The DoD uses the properties of these orbital regions for the implementation of their satellite programs. GEO is used extensively for communications and C4ISR satellites, while MEO is preferred for Global Positioning System (GPS) satellites. I examined seven DoD satellite acquisition programs, five GEO (three C4ISR and two communication), and two MEO GPS programs.

a. *Space Based Infrared Systems (SBIRS) High*

The Space Based Infrared Systems (SBIRS) High program is an integrated system consisting of multiple space and ground elements. The constellation architecture for SBIRS High (occasionally referred to as SBIRS GEO) includes GEO satellites (with highly elliptical orbit (HEO) sensors), ground stations, and communication links. SBIRS is a key C4ISR system that is part of North America's missile early warning and defense systems. The SBIRS constellation consists of infrared (IR) sensor payloads on host satellites in HEO and two IR sensors each on dedicated SBIRS satellites in GEO

(Department of Defense, 2011e). My research focused on the procurement of the six GEO satellites: two research, development, test & evaluation (RDT&E) satellites, and four procurement satellites in orbit.

b. Transformational Satellite Communications System (TSAT)

The Transformational Satellite Communications System (TSAT) provides high data rate military satellite communications (SATCOM) services to the DoD. TSAT is a key to global net-centric operations. As the spaceborne element of the Global Information Grid (GIG), it extends the GIG and provides improved connectivity and data transfer capability to the users without terrestrial connections. Utilizing Internet Protocol (IP) routing, it connects thousands of users through networks rather than limited point-to-point connections. TSAT enables protected communications on the move (COTM) to small highly mobile users and provides high data rate connections to ISR platforms. TSAT provides extremely high frequency (EHF), X-band, Ka-band, and laser services. The TSAT program consists of a five-satellite constellation (with a sixth satellite procured to ensure mission availability), TSAT Satellite Operations Centers (TSOC) for on-orbit control, TSAT Mission Operations Systems (TMOS) for network management, and ground gateways. The terminal segment provides users with access to space C4ISR products and services (Department of Defense, 2004). My research focused on the procurement of the six GEO satellites.

c. Advanced Extremely High Frequency Satellite (AEHF)

Advanced Extremely High Frequency (AEHF) is a joint Service satellite communications system that provides global, secure, protected, and jam-resistant communications for high priority military ground, sea, and air assets. It is the *Next-Stage C4ISR Bandwidth* satellite program to form the secure, hardened backbone of the Pentagon's future military SATCOM programs after the cancellation of the higher capacity TSAT program (Defense Industry Daily, 2012). The system consists of four satellites in a GEO constellation that provides continuous EHF extended data rate (XDR) coverage between 65 degrees north and 65 degrees south latitude. The AEHF operational system is composed of three segments: space (the satellites); mission control (with

associated communications links); and terminals (the users). The space segment consists of a cross-linked constellation of satellites to provide worldwide coverage. The mission control segment controls satellites on orbit, monitors satellite health, and provides communication system planning and monitoring. The terminal segment includes fixed and mobile ground terminals, ship and submarine terminals, and airborne terminals (Department of Defense, 2011a). My research focused on the procurement of the six GEO satellites: two RDT&E satellites, and four procurement satellites in orbit.

d. Mobile User Objective System (MUOS)

Mobile User Objective System (MUOS) is a narrowband military SATCOM system that supports a worldwide, multi-Service population of mobile and fixed-site terminal users in the ultra-high frequency (UHF) band, providing increased communications capabilities to smaller terminals while still supporting interoperability to legacy terminals. MUOS adapts a commercial third generation wideband code division multiple access (WCDMA) cellular phone network architecture and combines it with GEO satellites (in place of cell towers) to provide a new and more capable UHF military SATCOM system. MUOS includes operational satellites, a ground control and network management system, and a new waveform for user terminals. The space portion is comprised of a constellation of four GEO satellites. The ground system includes the transport, network management, satellite control, and associated infrastructure to both fly the satellites and manage the users' communications (Department of Defense, 2011c). My research focused on the procurement of the four GEO satellites.

e. Wideband Global SATCOM (WGS)

Wideband Global SATCOM (WGS) augments the Defense Satellite Communications System III (DSCS III), and the Global Broadcast Service Phase II. WGS is a fully duplexed communications platform offering warfighters a significant increase in capacity, connectivity, and interoperability. It provides high-capacity and digitally channelized service at both X and Ka frequency bands, opening up a new two-way Ka communication capability. This highly flexible communications satellite design leverages commercial processes, practices, and technology to provide a wideband

payload compatible with existing and future terminals. The costs associated with this acquisition are greatly reduced compared to comparable programs through an international partnership cooperative agreement in exchange for access to the WGS constellation. Member countries include Australia, Canada, Denmark, Luxembourg, the Netherlands, and New Zealand (Department of Defense, 2011f). My research focused on the procurement of the eight GEO satellites.

f. Navstar Global Positioning System (NAVSTAR GPS)

The Navstar Global Positioning System (Navstar GPS) is a space-based radio positioning, navigation, and time distribution system. The modernized portion of the program is often referred to as GPS IIF. GPS IIF consists of twelve satellites and provides improved accuracy, greater security, anti-jam capabilities, and a dedicated civilian safety-of-life signal, while maintaining baseline legacy GPS performance. Military mission areas supported include navigation and position fixing; air interdiction; close air support; special operations; strategic attack; counter-air and aerospace defense; theater and tactical command, control, communications and intelligence; precision munitions guidance; and ground/sea warfare. GPS IIF also carries a suite of nuclear detonation detection system sensors as a secondary payload. These sensors provide worldwide, near real-time, three-dimensional location of nuclear detonations (Department of Defense, 2011d). My research focused on the procurement of the 12 MEO satellites, GPS IIF.

g. Global Positioning System III (GPS IIIA)

GPS is a satellite-based radio navigation system that provides precise, continuous, all-weather, common-grid positioning, velocity, navigation, and time reference capability to civil, commercial, and military users worldwide. It provides signals users can process to determine accurate position, velocity, and time. GPS III is the next generation of space vehicle (SV) that provides an international standard available on a continuous worldwide basis free of direct user fees. The first eight satellites, SVs 01–08, are the part of the program known as GPS IIIA. The program provides increased anti-jam power to the Earth coverage M-code signals and a capability to insert future

capabilities with the acquisition of additional SVs (Department of Defense, 2011b). My research focused on the procurement of the eight MEO satellites, GPS IIIA.

3. DoD Satellite System Comparison

I examined seven DoD satellite acquisition programs, five GEO (three C4ISR and two communication) and two MEO GPS programs, to understand and quantify the following parameters: production time, total cost, unit cost, and design life.

I calculated production time from the year the requirements document was signed, to the year when the system achieved, or was projected to reach, full operational capability (FOC).

The total cost used in this project was specifically the defense acquisition-defined² program acquisition cost. Program acquisition cost is a multi-appropriation cost. It consists of the estimated cost of development RDT&E, procurement, and system-specific military construction (MILCON) necessary to acquire the defense system. RDT&E costs are accumulated from the point in time when the DoD acquisition program is designated by title as a program element or major project within a program element. Military construction costs include only those projects that directly support and uniquely identify with the system. This is the complete cost (total cost) of acquiring a weapon system that is ready to operate.

It is important to emphasize that program acquisition cost is only the cost of acquiring a satellite system; it does not include launch and support costs. Procurement of satellites and launch services are funded separately – typically two years prior to launch. Generally speaking, the first two satellites of a new system are purchased with RDT&E funding and the remainder of the satellites are purchased with procurement funding. Also funded separately, support costs are funded subsequent to program acquisition and launch. As an example of the relative expense of each cost, the 2013 costs for space-based and related systems are: satellites \$4.1 billion; support \$2.1 billion; and launch \$1.8 billion (Department of Defense, 2012).

² Glossary of Defense Acquisition Acronyms and Terms, Fourteenth Edition, July 2011. Retrieved from: <https://dap.dau.mil/glossary/pages/2464.aspx>

The unit cost used in this project was specifically the defense acquisition-defined³ program acquisition unit cost (PAUC). PAUC is computed by dividing the program acquisition cost (total cost) by the program acquisition quantity (number of satellites). Program acquisition quantity is the total number of fully configured end items, to include research and development (R&D) units, a DoD component intends to buy through the life of the program (number of satellites), as approved by the Under Secretary of Defense for Acquisition, Technology, and Logistics (USD[AT&L]). This quantity may extend beyond the Future Years Defense Program (FYDP) years but shall be consistent with the current approved program. The PAUC and average procurement unit cost (APUC) are the subject of the unit cost reports (UCRs). Programs for which the current estimate of either the PAUC or APUC has increased by 15% or more over the currently approved acquisition program baseline (APB) must report a unit cost breach to the congressional defense committees.

From this data, I calculated the yearly cost for the system over the system's design life cycle by dividing the total cost by the system life. Then I calculated the yearly cost for the system over the system's design life cycle for an individual satellite by dividing the yearly cost by the number of satellites. My findings are summarized in Table 1.

All of the cost numbers are in 2011 U.S. dollars. Only the C4ISR system types were include in the GEO average calculation. The WGS system cost data appears anomalous because the costs associated with the program were greatly reduced compared to comparable programs through an international partnership cooperative agreement in exchange for access to the WGS constellation.

³ Glossary of Defense Acquisition Acronyms and Terms, Fourteenth Edition, July 2011. Retrieved from: <https://dap.dau.mil/glossary/pages/2466.aspx>

Table 1. A Time and Cost Comparison of DoD Satellite Systems in GEO and MEO

System	Type	Orbit	# of Sats	Production Time (Years)	Total Cost \$M	Unit Cost \$M	System Life (Years)	Yearly Cost \$M	Yearly Cost per Sat \$M
SBIRS	C4ISR	GEO	6	22	17699.8	2949.97	12	1474.98	245.83
TSAT	C4ISR	GEO	6	17	18920.7	3153.45	14	1351.48	225.25
AEHF	C4ISR	GEO	6	17	13474.2	2245.70	14	962.44	160.41
MUOS	Comm	GEO	4	15	7036.6	1172.77	14	502.61	125.65
WGS	Comm	GEO	8	15	3868.4	483.55	14	276.31	34.54
GEO Average*			6	18.7	16698.2	2783.04	13.3	1262.97	210.49
NAVSTAR	GPS	MEO	12	12	6581.4	199.44	12	548.45	45.70
GPS III	GPS	MEO	8	12	1469.3	521.16	15	97.95	12.24
MEO Average			10	12	4025.4	360.30	13.5	323.20	28.97

*C4ISR system types only

From Table 1, an empirical analysis would indicate that placing satellites in lower orbits produces several desirable results in all but one category. The production time for smaller satellites in a lower orbit is significantly less, and both the total cost and the unit cost are lower. Additionally, with the system design life being approximately equal for both orbits, the smaller satellite in a lower orbit also provides a lower yearly cost over the system design life cycle, and a lower yearly cost over the system design life cycle for an individual satellite. One notable exception to the across-the-board benefits of the MEO satellites is the number of satellites required. Because of their closer proximity to Earth and subsequent faster velocity, more satellites are required to attain the same coverage area provided by GEO satellites. From Table 1, it takes nearly double the number of MEO satellites compared to GEO satellites. Despite the greater number of satellites required, the MEO satellite total cost is still far less than the GEO satellite system because the unit cost is still far less for the smaller MEO satellites.

Less expensive satellites and less expensive satellite systems that can be produced faster are desirable attributes and would seem to obviate the production of GEO satellites. However, they are conducting different missions. The GEO satellites are providing C4ISR (the focus of this project) and communication functions, while the MEO satellites are providing GPS capability. Further investigation is warranted to preclude a deductive

fallacy that indicates the LEO satellites would follow the time and cost extrapolation and be even cheaper than the MEO satellites and faster to produce. Additionally, as the GEO and MEO satellites are conducting different mission, LEO satellites must be able to fulfill the desired C4ISR mission. My proposed systems in this project address both the cost and mission issues.

B. PROPOSED SATELLITE SYSTEMS

By using systems engineering and implementing a progressive evaluation plan—from conceptual design to preliminary system design, and from detailed design and development to production and system utilization—the program attains increased confidence in the technical solution and minimizes the costs associated with incorporating changes and system modifications. Waiting until later in the life cycle before detecting a potential problem, and having to incorporate a late change, can be costly. Thus, the implementation of a progressive and evolving plan is preferred by both PMs and engineers, with the objective to commence with the satellite performance validation effort as early as possible, providing that the results are meaningful overall.

It is important to emphasize the significance of reliability within the total spectrum of the design-related requirements and activities necessary in order to meet the systems engineering objectives. In the past, engineering emphasis has been placed primarily on determining the reliability requirements for the various individual elements of a system versus addressing the requirements for the system as an entity and integrating those requirements at the system level, as well as on integrating the reliability requirements pertaining to the people, facilities, data/information, processes, and the like. From a systems engineering perspective, the reliability of all the elements of a system should be considered as an integrated entity (T. Huynh, personal communication⁴, May 2011).

⁴ From class lecture notes: *Systems Engineering for Acquisition Managers* (SE4011), Department of Systems Engineering, Naval Postgraduate School.

1. Low Earth Orbit (LEO)

Most scientific satellites and many weather satellites are in a nearly circular, low Earth orbit. The satellite's inclination depends on what the satellite was launched to monitor. A satellite launched to monitor rainfall in the tropics, for example, would have a relatively low inclination (35 degrees), staying near the equator to allow its instruments to concentrate on the tropics as depicted in Figure 4.

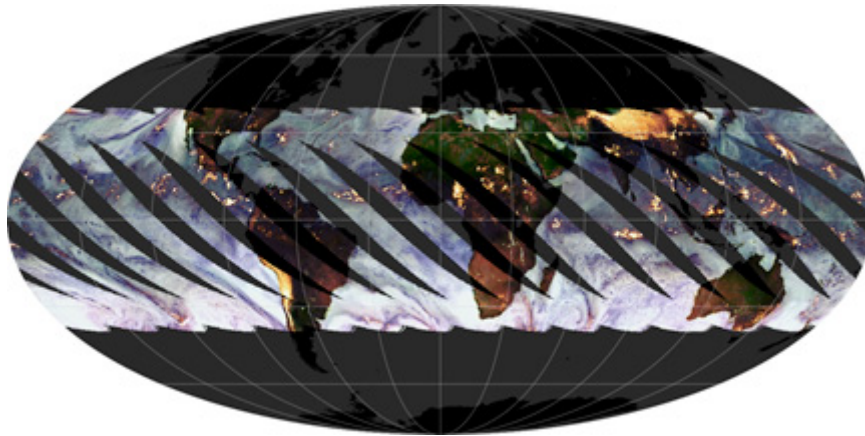


Figure 4. A Sample Image Depicting One Half of the Observations Made in a Single Day by a Low Inclination LEO Satellite (From Riebeek & Simmon, 2009)

Conversely, many satellites used to observe Earth have a nearly polar orbit. In this highly inclined orbit, the satellite moves around the Earth from pole to pole. During one half of the orbit, the satellite views the daytime side of the Earth. At the pole, the satellite crosses over to the nighttime side of Earth. As the satellites orbit, the Earth turns underneath. By the time the satellite crosses back into daylight, it is over the region adjacent to the area seen in its last orbit. In a 24-hour period, polar orbiting satellites will view most of the Earth twice: once in daylight and once in darkness.

Just as the GEO satellites have a sweet spot over the equator that lets them stay over one spot on Earth (geostationary orbit), the polar-orbiting satellites have a sweet

spot that allows them to stay in one time. This orbit is a sun-synchronous orbit, which means that whenever and wherever the satellite crosses the equator, the local solar time on the ground is always the same.

Because LEO orbits are not geostationary, a network (or “constellation” or “cluster”) of satellites is required to provide continuous coverage. Lower orbits aid remote sensing satellites because of the added detail that can be gained. Remote sensing satellites can also take advantage of sun-synchronous LEO orbits at an altitude of about 800 km (500 mi) and near polar inclination. The Environmental Satellite (Envisat) launched by the European Space Agency (ESA) is one example of an Earth observation satellite that made use of this particular type of LEO to service the continuity of European Remote-Sensing Satellite missions, providing additional observational parameters to improve environmental studies.

2. CubeSat Architecture

In a separate but related research effort, I recommend a multi-INT data collection system-of-systems infrastructure for low-cost, low-latency, cross-communicating, small modular LEO satellites for improved intelligence collection and satellite systems acquisition (Staab, 2012). The proposed network of satellite nodes can collect and process intelligence information autonomously at the satellite node, and thus minimize data transmission to Earth. Additionally, this minimizes the power requirements onboard satellites for transmission, making it possible for a small, low-power, bandwidth-limited nanosatellite to provide a low-cost, fast-to-orbit solution to replace large, high-power, high-bandwidth (but expensive) GEO satellites.

A LEO satellite constellation architecture is well suited for use in multi-INT data collection and transmission to Earth. A satellite in LEO is also well positioned to obtain high-quality, remote-sensing data. Not all satellites need to communicate with receiving stations on Earth—they just need to communicate with each other, with selected satellites used for transmitting to receiving stations on Earth. This constellation architecture contains multiple nodes that all collect and process multi-INT data, cross-communicate that information with other nodes, then send the information to Earth through a master

node. This architecture provides for true global coverage and allows mission operators to access processed information directly, bypassing the very slow and manpower-intensive data processing that would have otherwise been required by analysts at an intelligence center. Finally, this setup enables multiple missions to share the satellite data.

One nanosatellite that is currently available commercially is the CubeSat (Cuboid Satellite spacecraft unit), shown in Figure 5. The CubeSat offers a modular, scalable, and standardized plug-and-play design that suits the needs of the proposed satellite constellation. Individual CubeSat mobile nodes are configured with one or more sensors and internal module processing cards.

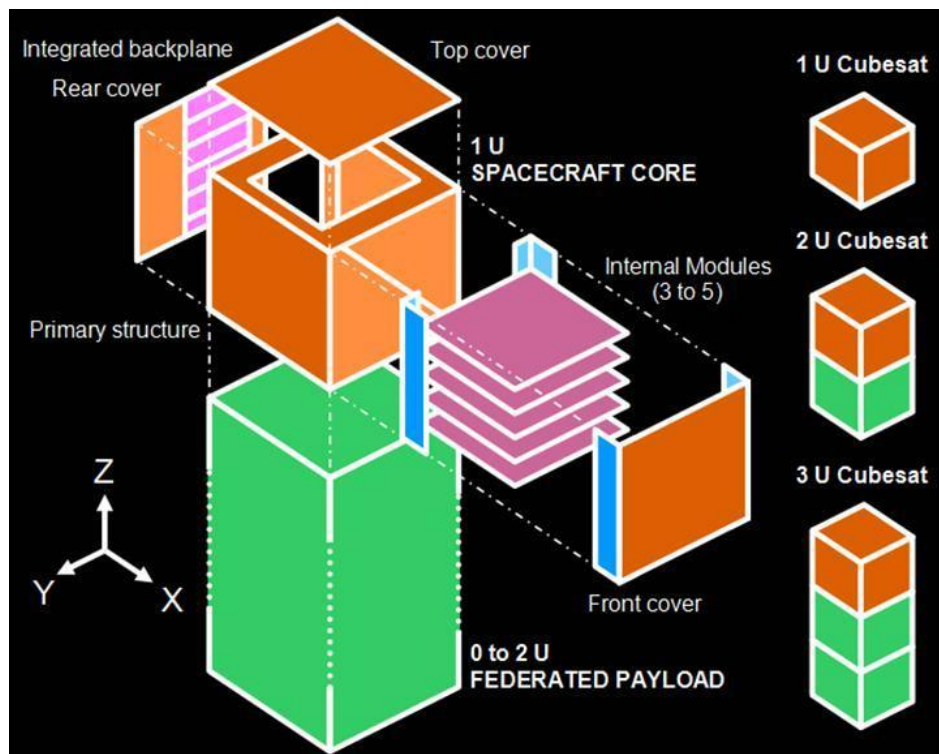


Figure 5. A Depiction of the Commercially Available CubeSat's Modular, Standardized, Plug-and-Play Design (From Clyde Space, 2012)

With regard to modularity, the internal modules have three to five slots available for processors and command and control (C2). The C2 module occupies one of the modules and the transceiver occupies a second module for sensor collection and crosslinking, leaving modules three through five available for data processing.

With regard to scalability, the CubeSat can vary in size by connecting units together. The base unit size is a “1U” CubeSat (1 unit Cuboid Satellite spacecraft unit) and has a form factor of 1 kg and 100 x 100 x 100 mm. This scalable CubeSat design allows for flexibility in the use of satellite constellation employment. A larger 3U CubeSat (three CubSats connected together to form one satellite) can be used to produce more power and to allow for the additional transceiver modules to communicate with additional nodes or for slightly larger transceivers with larger bandwidth capability (and greater power consumption) to be installed. Furthermore, a 3U CubeSat has more battery capacity to help ensure that the master node remains active during periods in which power production is limited by the lack of solar energy to the photovoltaic solar panels.

3. System F6 Architecture

The Defense Advanced Research Project Agency (DARPA) System F6 Program⁵ seeks to demonstrate the feasibility and benefits of a LEO satellite architecture wherein the functionality of a traditional “monolithic” spacecraft is delivered by a cluster of wirelessly interconnected modules capable of sharing their resources and utilizing resources found elsewhere in the cluster. Such architecture enhances the adaptability and survivability of space systems, while shortening development timelines and reducing the barrier to entry for participation in the national security space industry.

The program seeks to enable the emergence of a space “global commons” which would enhance the mutual security posture of all participants through interdependence. A key program goal is the industry-wide promulgation of open interface standards for the sustainment and development of future fractionated systems and low-cost commercial hardware for the sustained development of future fractionated systems beyond the

⁵ This material is declared a work of the U.S. government and is not subject to copyright protection in the United States.

System F6 demonstration (F6 is an acronym for Future, Fast, Flexible, Fractionated, Free-Flying Spacecraft united by Information eXchange). A depiction of the proposed System F6 architecture is provided in Figure 6.

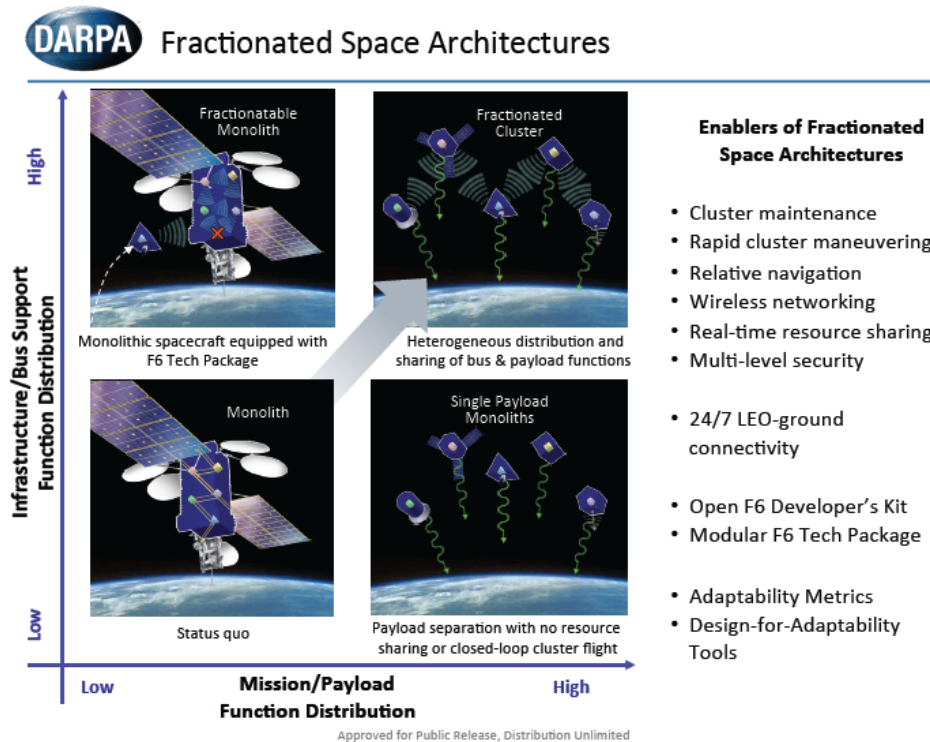


Figure 6. A Depiction of the Proposed System F6 Architecture (From Eremenko, 2011)

Two key artifacts will be developed in the course of the program. The first is the F6 Developer's Kit (FDK), which is a set of open-source interface standards, protocols, behaviors, and reference implementations, necessary for any party, without any contractual relationship to any System F6 performer, to develop a new module that can fully participate in a fractionated cluster. The second is the F6 Technology Package (F6TP), which is a hardware instantiation of the wireless connectivity, packet-switched routing, and encryption capable of hosting the protocol stack and resource-sharing and cluster flight software needed to enable an existing spacecraft bus to fully participate in a fractionated cluster. In essence, the F6TP is a hardware instantiation of the FDK.

4. Space Enabled Effects for Military Engagements (SeeMe) Architecture

Today, the lowest echelon members of the U.S. military deployed in remote overseas locations are unable to obtain on-demand satellite imagery in a timely and persistent manner for pre-mission planning or intelligence updates. This is due to lack of satellite over-flight opportunities, inability to receive direct satellite downlinks at the tactical level, and information flow restrictions.

Another DARPA project, the Space Enabled Effects for Military Engagements (SeeMe) Program,⁶ aims to provide mobile individual U.S. warfighters access to on-demand, space-based tactical information in remote and beyond-line-of-sight conditions as depicted in Figure 7.

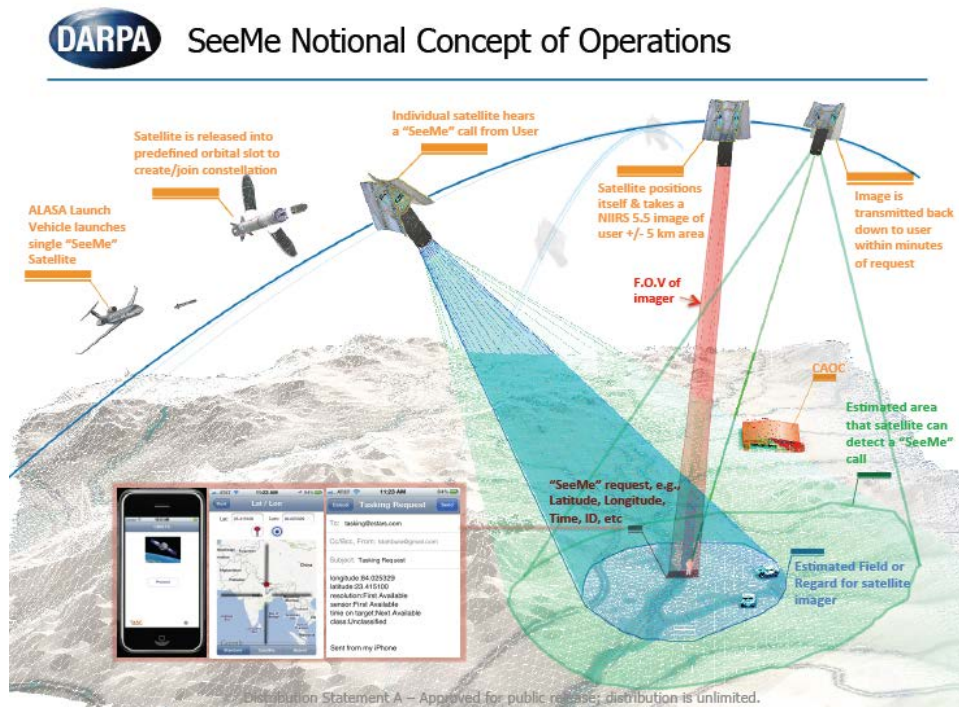


Figure 7. A Depiction of the SeeMe Notional Concept of Operations (From Barnhart, 2012)

⁶ This material is declared a work of the U.S. government and is not subject to copyright protection in the United States.

If successful, SeeMe will provide small squads and individual teams the ability to receive timely imagery of their specific overseas location directly from a small satellite with the press of a button—something that is currently not possible from military or commercial satellites.

The program seeks to develop a constellation of small “disposable” satellites, at a fraction of the cost of airborne systems, enabling deployed warfighters overseas to access SeeMe on existing handheld devices to receive a satellite image of their precise location within 90 minutes. DARPA plans SeeMe to be an adjunct to UAV technology, which provides local and regional very high resolution coverage, but cannot cover extended areas without frequent refueling. SeeMe aims to support warfighters in multiple deployed overseas locations simultaneously with no logistics or maintenance costs beyond the warfighters’ handheld devices.

The SeeMe constellation may consist of some two-dozen satellites, each lasting 60–120 days in a very low Earth orbit before de-orbiting and completely burning up, leaving no space debris and causing no re-entry hazard. It is designed to be produced in three months, with a cost goal of \$500,000 or less per satellite at production rate. Using this structure, the system is designed to conform to an actual DoD tempo for contingency operations (approximately 90 days planning and 90 days operational), as opposed to conforming to the satellite and its life optimization.

The program may leverage DARPA’s Airborne Launch Assist Space Access (ALASA) program, which is developing an aircraft-based satellite launch platform for payloads on the order of 100 lb_m. ALASA seeks to provide low-cost, rapid launch of small satellites into any required orbit, a capability not possible today from fixed ground launch sites.

My research focused on the conservative estimates of 24 satellites, with a production time of 90 days, at a cost of \$500,000 per satellite, and a system life of 90 days.

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IV. ANALYSIS AND CONCLUSIONS

In Chapter III Section A, I examined the current acquisition process and system engineering approach to multi-INT data collection via satellite. I identified and enumerated the current C4ISR acquisitions process, specifically focusing on time (production time and system life) and cost. Additionally, in Chapter III Section B, I introduced several proposed low latency, cross-communicating, modular LEO satellite systems for improved multi-INT data collection.

A. ANALYSIS

1. Time and Cost Savings

For my system comparison of current GEO and proposed LEO C4ISR satellites, I focused on the same parameters of time (production time and system life) and cost, using the GEO and MEO averages attained in Table 1, and the projected LEO estimates from the SeeMe program. My findings are summarized in Table 2.

Table 2. A Time and Cost Comparison of DoD Satellite Systems in GEO and LEO

System Type & Orbit	# of Sats	Production Time (Years)	Total Cost \$M	Unit Cost \$M	System Life (Years)	Yearly Cost \$M	Yearly Cost per Sat \$M
C4ISR GEO Average*	6	18.7	16698.2	2783.04	13.3	1262.97	210.49
GPS MEO Average*	10	12	4025.4	360.30	13.5	323.20	28.97
C4ISR LEO per Mission	24	0.25	12.0	0.50	0.25	12.00	0.50
20 LEO Missions	480	0.25	240.0	0.50	0.25	240.00	0.50
40 LEO Missions	960	0.25	480.0	0.50	0.25	480.00	0.50
80 LEO Missions	1920	0.50	960.0	0.50	0.25	960.00	0.50

*Data from Table 1

It is immediately striking that again, as discovered in Table 1, placing satellites in lower orbits produces several desirable results in all but two categories: system life and number of satellites. The production time for LEO satellites in a lower orbit is

dramatically less, and both the total cost and the unit cost are lower. Additionally, the LEO satellite in a lower orbit also provides a lower yearly cost over the system design life cycle, and a lower yearly cost over the system design life cycle for an individual satellite. However, yearly costs must be considered differently for the LEO C4ISR application because of system life.

As discussed earlier, the LEO satellite cluster architecture redefines the C4ISR system paradigm. The current system focus is on the satellite, not the mission, thereby creating a different requirement for system life. Satellites are currently built to achieve a long, reliable, safe system life, resulting in marginal systems that need several redesigns or major changes to achieve functionality, thus increasing system development time and cost, and unit production cost. The systems that I have proposed are designed to conform to an actual DoD operational tempo of 90–180 days for contingency operations. In this system, the unit cost at production rate is fixed and remains constant. This fixed unit cost produces two results: the yearly cost per satellite is fixed and remains constant; and the yearly cost is equivalent to the total cost. Utilizing a system based on mission needs, only the amount of satellites required to fulfill the mission are procured each year. Therefore, yearly costs fluctuate in my proposed systems based on mission needs.

In this new system, one 90-day mission requires a cluster of 24 satellites. Each 90-day mission, therefore, costs \$12 million (24 satellites at \$0.5 million each) as shown in Table 2. To illustrate the practicable savings of my proposed system in which only the amount of satellites required to fulfill the mission are procured each year, I will provide three examples. If for example, in a given year there is a requirement for 1800 days of coverage (e.g., twenty 90-day missions or ten 180-day missions), requiring 480 satellites (one 24-satellite constellation for each 90-day period of coverage), the yearly cost would be \$240 million for that year, shown in Table 2 as *20 LEO Missions*, but it would remain well below the \$1.26 billion cost of a GEO satellite system for that same year. Suppose that in the following year, the requirement doubles. Now the requirement is for 3600 days of coverage (e.g., forty 90-day missions, twenty 180-day missions, or ten full-year missions), requiring 960 satellites. The yearly cost would then double to \$480 million for that year, shown in Table 2 as *40 LEO Missions*, but it would again remain well below

the \$1.26 billion cost of a GEO satellite system for that same year. In the following year, the requirement doubles yet again. Now the requirement is for 7200 days of coverage (e.g., eighty 90-day missions, forty 180-day missions, or twenty full-year missions), requiring 1920 satellites. The yearly cost would then double again to \$960 million for that year, shown in Table 2 as *80 LEO Missions*, but it would again remain below the \$1.26 billion cost of a GEO satellite system for that same year. Indeed, the LEO mission requirement would need to rise to 2526 satellites in a year, or 9540 days of coverage (e.g., one hundred and six 90-day missions, fifty-three 180-day missions, or twenty-seven full-year missions), to exceed the yearly cost of a GEO satellite system.

The extrapolation of mission requirement scenarios in the examples provided highlights two key factors associated with this new system that conforms to an actual DoD operational tempo of 90–180 days for contingency operations. First, the new system provides lower yearly costs for all mission needs that cumulatively and collectively require less than 2526 satellites in a year. Second, production capacity must be considered when determining production time. Production time will increase once maximum production capacity has been reached. Production capacity should therefore be determined by a statistical analysis of 90-day mission requirement historical data. If for example, the maximum 90-day mission usage is determined to be 3600 days of coverage (i.e. forty 90-day missions) requiring 960 satellites, production capacity should be set at 960 satellites per 90-day production period. If this production capacity is exceeded, production time will begin to increase with the number of satellites required to meet mission needs. If for example, in a given year there is a requirement for 7200 days of coverage (e.g., eighty 90-day missions or forty 180-day missions), requiring 1920 satellites, the production time would double to 180 days, shown in Table 2 as *80 LEO Missions*. With production capacity set at 960 satellites per 90-day production period as in the example, the proposed LEO system could sustain 40 year-long missions (producing 3840 total satellites), continuously throughout an entire year.

The other exception to the across-the-board benefits of LEO satellites is the number of satellites required. Despite the greater number of satellites required, the LEO satellite total cost is still far less than the GEO satellite system because of the extremely

low, fixed unit cost. These low-cost, fast-production satellites can be used to provide C4ISR and communication functions currently provided by GEO satellite systems.

Another important cost saving is found in system size and weight. The massive SBIRS GEO C4ISR satellite dimensions are 7 ft x 6.3 ft x 19.7 ft (stowed) and 48.6 ft x 22.4 ft x 19.7 ft (deployed). The launch weight is 10,656 pounds (4,833 kilograms) and the on-orbit weight is 5,603 pounds (2,547 kilograms). In stark contrast, a CubeSat cuboid spacecraft unit has a form factor of 100 mm³ and weighs only 1 kg. Similarly, the SeeMe satellite is designed to be compatible with the ALASA delivery vehicle at roughly 20–30 inches in diameter and 20–32 inches in length +/- 25%, and a weight of 45 kg.

The size and weight cost savings are found in both the reduction of expensive construction materials, and in the fuel costs of placing the space vehicle in orbit. The fuel costs are reduced two ways for the LEO satellite. First, the smaller satellites require less fuel because they weigh less. Second, they require less fuel because they are traveling a shorter distance: 320–400 km for the International Space Station (ISS) in LEO, as opposed to 35,786 km for a geostationary GEO. As noted in Chapter III Section A, the 2013 launch cost for space-based and related systems is nearly half the cost (44%) of acquiring current DoD satellite systems. Although funded separately, they are both part of the DoD budget. Therefore, any success in reducing the size and weight of current systems will not only decrease acquisition costs, it will also dramatically decrease the launch costs that are drawn from the aggregate DoD budget.

In addition to the cost savings found in production, launch, and maintenance, a militarily significant cost savings is replacement cost due to enemy action. The complex, large GEO satellite presents a lucrative target to an enemy and could be destroyed or rendered inoperative by a single missile strike. Conversely, the proposed small-satellite cluster would be difficult to detect, but even if detected it would be infeasible to destroy an entire cluster, or multiple clusters servicing multiple missions. Considering unit cost, the loss of a single GEO satellite would be enormous. Considering the production time of the GEO satellite, the effect of losing of a single satellite would be devastating to the DoD's warfighting capability. From a military engagement perspective, time and cost savings again favor the utilization of a small, distributed, multiple-target cluster of

relatively inexpensive, quickly produced, fast-to-orbit satellites. Such a system would be more difficult to detect, engage and destroy, and would also be relatively quick and inexpensive to replace when compared to the GEO systems currently in use.

2. MUIRS Attributes

A maintainability, upgradeability, interoperability, reliability, and safety/security (MUIRS) analysis of low latency, cross-communicating, modular LEO satellites for improved multi-INT data collection reveals benefits in all categories. The improvements in the first four MUIRS categories are facilitated by the LEO system's brief system life—an attribute that initially seemed undesirable, but that was ultimately revealed to be perfectly suited to the newly proposed paradigm of producing systems designed with a focus on the mission, not the satellite.

Maintainability concerns are essentially eliminated for the LEO satellite constellation architecture. Small modular LEO satellites have a short life cycle and do not require maintenance once in orbit. Instead of struggling for fourteen years to maintain a GEO satellite that is orbiting over 22,000 miles from Earth, the proposed LEO system is designed to last only 60–120 days before de-orbiting and completely burning up, leaving no space debris and causing no re-entry hazard.

Upgradability is inherent in the proposed LEO satellite systems. Their short system life requires them to be replaced frequently and enables frequent upgrades. A LEO satellite cluster can be in orbit within 90 days loaded with the latest cutting-edge hardware and software technology, whereas an end-of-life GEO asset is relying on technology that is over a decade old (with the exception of some software upgrades that can be accomplished through remote access). With technological capability doubling every two years as observed in Moore's law, GEO satellite capabilities are nearly obsolete while the system is still in use.

Interoperability is similarly refreshed frequently as new standards are developed. Each new generation of satellites incorporates updates to maintain interoperability with new technologies in a constantly changing net-centric environment. A pre-Internet GEO satellite would not be configured to accommodate IP traffic for example.

Reliability concerns, like the maintainability attribute, are nearly eliminated for the LEO satellite architecture. An architecture that utilizes a cluster of cross-communicating modular satellites allows for a scalable distribution of the processing resources in small satellites needed to produce the results that can be attained with a single large satellite. In this distributed architecture, the reliability required of each individual cross-communicating small satellite is far less than that required of a single large satellite—any failed satellite within the constellation can be compensated by another satellite in its network. The GEO satellite architecture is also more vulnerable to data integrity loss and data interception because of the constant communication to terrestrial base stations. Additionally, these traditional GEO satellites need to be built to extremely high reliability standards due to massive repair and replacement costs.

Safety and security is also increased for LEO C4ISR satellites because of the distributed constellation architecture. One of the primary objectives of the System F6 program is to explore the benefits of a LEO satellite architecture wherein the functionality of a traditional “monolithic” spacecraft is delivered by a cluster of wirelessly interconnected modules capable of sharing their resources and utilizing resources found elsewhere in the cluster. Such architecture enhances the adaptability and survivability of space systems, while shortening development timelines and reducing the barrier to entry for participation in the national security space industry. As in other basic military applications, a small, distributed, multiple-target cluster of satellites that can be quickly launched into LEO travelling at over 17,000 mph presents a more difficult and less lucrative target than a single, massive satellite in GEO.

B. CONCLUSIONS

The current acquisition process for C4ISR GEO satellites is inadequate when compared to the proposed LEO satellite architectures. The proposed low latency, cross-communicating, modular LEO satellite systems for improved multi-INT data collection presented in this project provide benefits in all of the areas evaluated. Specifically, production time, cost, MUIRS attributes, and system life all favor the proposed LEO satellite architecture.

The production time for LEO satellites in a lower orbit is dramatically less; LEO satellites are designed to be produced in three months, while GEO satellite production time averages over 18 years. Total cost and unit cost are lower for the LEO proposals. The yearly cost over the system design life cycle, and the yearly cost over the system design life cycle for an individual satellite are also lower for the LEO proposals. Additionally, cost savings are found in the LEO architecture through the reduction of expensive construction materials, and in reduced fuel costs when placing the space vehicle in orbit. Small LEO satellites require less fuel because they weigh less and they are traveling a shorter distance during a much shorter duration (LEO versus GEO).

MUIRS attributes are facilitated by the LEO system's brief system life. Maintainability concerns are essentially eliminated for the LEO satellite constellation architecture that is designed to last only 60–120 days before de-orbiting and completely burning up upon re-entry. Upgradability is inherent; the short system life requires them to be replaced frequently and enables frequent upgrades with the latest evolution in militarily useful technology. Interoperability is similarly refreshed frequently to maintain interoperability with new technologies in a constantly changing net-centric environment. Reliability concerns are nearly eliminated in a distributed constellation architecture where the reliability required of each individual cross-communicating small satellite is far less in that any failed satellite within the constellation can be compensated by another satellite in its network. Safety and security is also increased using small, distributed, multiple-target clusters of wirelessly interconnected modules capable of sharing their resources and utilizing resources found elsewhere in the cluster.

Finally, the proposed architecture supports a new paradigm for improved multi-INT data collection through the utilization of low latency, cross-communicating, modular LEO satellite systems designed with a focus on the C4ISR mission, not the satellite and its life optimization. System life must be considered differently in this new paradigm. The ephemeral system life in the proposed systems initially seemed undesirable, but was ultimately revealed to be perfectly suited to the new paradigm that conforms to the actual DoD operational tempo for contingency operations. In this new system, the low yearly costs fluctuate based on mission needs.

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V. RECOMMENDATIONS AND SUMMARY

A. RECOMMENDATIONS

It is recommended that the Department of Defense consider a new paradigm for improved multi-INT data collection through low latency, cross-communicating, modular LEO satellite systems designed with a focus on the C4ISR mission, not the satellite and its life optimization. In this new paradigm, production time and system life conform to the actual DoD tempo for contingency operations regarding planning time and operational time, respectively.

The new system would result in smaller, faster-to-orbit satellites that provide the most state-of-the-art systems, specifically tailored for the assigned mission. They could be assembled from mostly off-the-shelf components in a plug-and-play fashion, depending on mission requirements, resulting in enormous savings—both total cost and unit cost—and such systems would achieve across-the-board MUIRS benefits while requiring less fuel to launch and achieve orbit.

B. SUMMARY

The use of satellites for multi-INT data collection allows the military to conduct C4ISR missions around the globe. However, the time and cost required to produce current systems are too great to meet operational needs and do not support MUIRS considerations. A transition is needed from the existing GEO satellite architecture to a constellation architecture of low latency, cross-communicating, modular LEO satellites.

After a literature review of supporting research, I investigated the GEO satellites used extensively by the DoD for communications and C4ISR satellites. I examined seven DoD satellite acquisition programs, five GEO (three C4ISR and two communication), and two MEO GPS programs. My examination and data analysis indicated that placing satellites in lower orbits produces several desirable results. The production time, total cost, and unit cost were all reduced. Additionally, the yearly cost for the system and the yearly cost for an individual satellite were reduced. However, I noted that lower orbits required more satellites.

I then introduced several proposed low latency, cross-communicating, modular LEO satellite systems for improved multi-INT data collection, and conducted a system comparison of current GEO and proposed LEO C4ISR satellites, focusing on the parameters of time (production time and system life) and cost, and included a MUIRS assessment.

The analysis results indicated that the proposed LEO satellite systems provided benefits in all of the areas evaluated; production time, cost, MUIRS attributes, and system life all favored the proposed architecture. The production time, total cost, and unit cost were all dramatically less, along with the yearly cost for the system and the yearly cost for an individual satellite. Additional savings were found in reduced construction and fuel costs. MUIRS benefits were derived from the LEO system's brief system life. Maintainability concerns are essentially eliminated, upgradability is inherent, and interoperability is similarly refreshed. Reliability concerns are nearly eliminated through redundancy, and safety and security is increased using a small, distributed constellation.

I then concluded that my proposed architecture supports a new paradigm for improved multi-INT data collection through the utilization of low latency, cross-communicating, modular LEO satellite systems designed with a focus on the C4ISR mission, not the satellite and its life optimization. In this new paradigm, production time and system life conform to the actual DoD tempo for contingency operations regarding planning time and operational time, respectively.

Finally, I recommended that the Department of Defense consider this new paradigm that would result in smaller, faster-to-orbit satellites that provide the most state-of-the-art systems, specifically tailored for the assigned mission requirements, resulting in enormous total cost and unit cost savings, and achieving across-the-board MUIRS benefits while requiring less fuel to launch and achieve orbit.

C. AREAS FOR FUTURE WORK

1. Engineering Development

Engineering areas for development are already underway as proposed in Chapter III Section B. Communication channels will need to be constantly updated and improved

to allow for greater bandwidth and IP-based connectivity for the satellite cluster's connection to Earth, and a cross-communicating, self-healing, ad-hoc network connection within the constellation. Power considerations must also be addressed to include reducing the power required of onboard components, and increasing power supply from advanced photovoltaics or advanced energy storage devices such as improved batteries or fuel cells. Launch vehicles must also be developed to accommodate frequent deployment of satellite constellations. Satellite constellation standards must be developed to ensure modular compatibility (within the system) and interoperability (between systems). Ground link systems must be developed to allow users on the ground to access the multi-INT C4ISR data with low latency and in a user friendly format. Finally, there is a need to continue the development of smaller and higher resolution sensors.

2. Defense Acquisition Program Management

The defense acquisition system also has several areas for development. Further investigation should be conducted regarding unit cost for the proposed systems. Specifically, the operational requirements introduced in Chapter IV Section A should be compared to nominal "peace-time" mission years, and high-use mission years that have been experienced in recent sustained overseas combat operations. This comparison could be used when evaluating the cross-over point (the example used in this project was a LEO mission requirement for 2526 satellites in a year, or 9540 days of coverage) where the yearly cost of the proposed systems exceeds the yearly cost of a current GEO satellite system. The technical and operational requirements must also be clearly defined for the proposed systems so that developmental testing (DT) parameters can be established to ensure the proposed systems meet the required technical specifications and so that operational testing (OT) parameters can be developed to fulfill all of the critical operational issues (COI) for the system.

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